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Response of carbon footprint of spring maize production to cultivation patterns in the Loess Plateau, China

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ABSTRACT

Agriculture is a primary contributor of greenhouse gas emissions and thus plays an important role in global climate change. Assessments of the carbon footprints of agricultural products are therefore helpful in climate change mitigation. The objective of this study was to provide a quantitative estimate of the carbon footprint of spring maize (*Zea mays* L.) production under different cultivation patterns. Four cultivation patterns were assessed in this study: traditional pattern, optimal pattern, super-high-yield pattern, and high-yield and high-efficiency pattern. The results showed that the greenhouse gas emissions from the agricultural inputs were 3225.2, 3152.9, 4557.2, and 4259.7 kg CO_2-eq ha^{-1} for the traditional, optimal, super-high-yield, and high-yield and high-efficiency patterns, respectively, in the spring maize production process. Fertilizers, including chemical fertilizers and organic fertilizer, predominated among the contributors of total greenhouse gas emissions from agricultural inputs, accounting for 66.8, 65.9, 76.1, and 74.4% among the traditional, optimal, super-high-yield, and high-yield and high-efficiency patterns, respectively. The carbon footprint per yield among different cultivation patterns ranged from 0.48 kg CO_2-eq kg^{-1} in the traditional pattern to 0.64 kg CO_2-eq kg^{-1} in the high-yield and high-efficiency pattern, with intermediate values for the super-high-yield and optimal patterns. The N_2O from soil and fertilizer application was the greatest contributor to the carbon footprint in spring maize production. Overall, higher yield and lower carbon footprint were concurrently observed under the super-high-yield pattern in the current study. Moreover, a reduction in the rate of fertilizers may provide a potential solution for reducing the carbon footprint of spring maize.

1. Introduction

Climate change has recently been an increasingly important focus for politicians, scientists, and the public. Anthropogenic greenhouse gas (GHG) emissions are main factors in climate change. Carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) are the top three anthropogenic GHG emissions resulting in climate change globally (Stocker et al., 2013). Agricultural activities accounted for 60% of N_2O and 50% of CH_4 emissions in a 2005 inventory of global GHG emissions (Smith et al., 2007), indicating that agriculture is one of the main contributors of GHG (Stocker et al., 2013). Thus, sustainable agriculture could also be an excellent solution for mitigating global warming by reducing the GHG emissions resulting from agricultural inputs and by sequestering atmospheric CO_2 in the soil and biota (Lal, 2004). Therefore, coordinated and focused efforts are needed to explore and develop appropriate practices related to cleaner agricultural production and more sustainable methods of mitigating GHG emissions (Lal, 2004; Zhang et al., 2013).

GHG emissions can be evaluated quantitatively by their carbon footprint (CF) as an environmental performance indicator (Weinheimer et al., 2010). The CF of a product is used to quantify the sum of GHG emissions and removals as CO_2 equivalents (CO_2-eq) in a product system to mitigate climate change (ISO 14067, 2013). The magnitude of the CF of an agricultural product depends on the amount of GHG emissions from all agricultural inputs including the non-CO_2 GHG emissions from arable soil that result from several human-induced activities, e.g., tillage, fertilizing, and harvesting. Currently, numerous agricultural studies have been carried out to assess the CF of agricultural products to quantity GHG emissions from agricultural production in different regions around

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the world (Dubey and Lal, 2009; Cheng et al., 2011). Moreover, assessing the CF of main crop products is commonly performed with a life cycle assessment (LCA) method, tracking the product from raw material exploitation of agricultural inputs to farm gate (Hillier et al., 2009). Adjusting farming practices (e.g., tillage, fertilizing) by evaluating the CFs of agricultural produce would supply a potential solution for reducing GHG emissions and mitigating climate change. Recently, several studies have assessed the CFs of field crops under different agricultural practices (Gan et al., 2012a, 2012b; Xue et al., 2014). Farming management practices have some obvious effects on the CFs of agricultural products (Gan et al., 2014), including tillage practices (Zhang et al., 2013; Xue et al., 2014), cropping systems (Gan et al., 2011), and nitrogen (N) fertilizer rates (Gan et al., 2012b; Wang et al., 2015). However, little information regarding the influence of integrated technologies with different farming management techniques on the CFs of crop products has been reported.

Maize (*Zea mays* L.) is one of the three largest food staples, playing a pivotal role in ensuring food safety and increasing farmer income in China. Maize accounts for ~45% (~1.68 Mha) of the total crop planting area and ~68% (~8.63 Mt) of the total crop production and is the most important food staple in the Shanxi province of the Loess Plateau (NBSC, 2016). In order to meet maize production needs, a multitude of agricultural inputs (e.g., fertilizers, seeds, pesticides, energy) are applied to improve crop yield and income in the region, resulting in a large amount of GHG emissions.

Therefore, reducing the GHG emissions resulted from maize production of different patterns is of considerable importance in mitigating climate change. In addition, cultivation patterns integrated several different farming management practices, such as implementing certain cultivated varieties, planting densities, and fertilizer applications. However, little information about the effects of different cultivation patterns on GHG emissions exists. Therefore, it is important to assess the CFs of maize and its components under different cultivation patterns to develop sustainable technologies for spring maize production and mitigate GHG emissions. The objective of this study was to assess the GHG emissions associated with agricultural inputs and the resulting CFs under different cultivation patterns and to identify C-friendly and cleaner cultivation technologies for the spring maize cropping system in the Loess Plateau, China.

2. Materials and methods

2.1. Site description

This experiment was carried out in the farming station of the Shanxi Agricultural University in Taigu (37°43′N, 112°58′E), Shanxi Province of North China in 2010. Spring maize is the principal grain crop in this region. The region has a humid continental climate with a mean annual temperature of 9.9 °C. The highest and lowest mean monthly temperature in 2010 were recorded in July (23.6 °C) and January (−6.2 °C), respectively. The annual precipitation and sunshine duration average 462.9 mm and 2550 h, respectively. The length of the frost-free period is 176 d in the region. The predominant soil at the experimental site is classified as calcic cinnamon soil, which developed from the loess parent material. Soil samples from a depth of 0–20 cm were collected from the experimental field and measured before applying treatments. The basic components of the soil included 25.87 g kg^{-1} soil organic matter, 1.14 g kg^{-1} total N, 19.17 mg kg^{-1} NO_3^-, 9.56 mg kg^{-1} NH_4^+, 28.70 mg kg^{-1} available phosphorus, and 136.50 mg kg^{-1} available potassium.

2.2. Experimental design and management

Optimizing the nitrogen rate and planting density are methods for achieving high yields of maize (Gao et al., 2012). Based on this, different cultivation patterns are used to achieve high efficiency and output in Shanxi Province. We selected four different cultivation patterns from other research results that have been popularized. For the experimental design, the four treatments were arranged in 15 m × 4 m plots in a randomized complete block design with three replicates (Fig. 1). The four cultivation patterns assessed in the study included traditional pattern (TP), optimal pattern (OP), super-high-yield pattern (SHYP), and high-yield and high-efficiency pattern (HYEP). Among them, traditional pattern is a common pattern for spring maize cultivation for local farmers in the Shanxi Province (Zhang, 2013). To satisfy the food demand of ever-growing human population, researchers believe that increasing both the fertilizer application (especially organic fertilizer) and planting density would be a positive way for maize yield improvement (Gao et al., 2012), according to which some cultivation patterns emerge and draw attentions (e.g. optimal pattern and super-high yield pattern). As scientific achievements, cultivation patterns (e.g. optimal pattern and super-high yield pattern) are gradually applied into large-scale production of maize in different regions and truly make a great contribution to local grain yield improvement. However, the super-high yield pattern is source and economic consuming due to large amount of fertilizer inputs. For higher production efficiency, modified cultivation pattern (high-yield and high-efficiency pattern) was designed with lower fertilizer application. Cultivation patterns may result in distinct GHG emissions due to the different amount of agriculture inputs.

A total of 600 kg ha^{-1} compound fertilizer, 130.5 kg ha^{-1} urea as basal fertilizer, and 325.5 kg ha^{-1} urea as topdressing were used in all TP plots, with a planting density of 37,500 plants ha^{-1}. For all OP treatments, 15,000 kg ha^{-1} poultry manure, 500 kg ha^{-1} compound fertilizer as basal fertilizer, and 325.5 kg ha^{-1} urea as topdressing were used, with a planting density of 45,000 plants ha^{-1}. For all SHYP and HYEP plots, 22,500 kg ha^{-1} poultry manure and 1000 kg ha^{-1} compound fertilizer were applied as basal fertilizer, with a planting density of 75,000 plants ha^{-1}. In addition, 450 kg ha^{-1} and 325.5 kg ha^{-1} urea were applied to SHYP and HYEP plots, respectively, as topdressing. Compound fertilizer ($N:P_2O_5:K_2O = 15:15:15$) and poultry manure were applied as basal fertilizer before sowing. Urea was used as basal fertilizer for TP and as topdressing in the jointing stage for other treatments. The cultivars were Jinyu 811 in all TP and OP plots and Dafeng 26 in all SHYP and HYEP plots. Detailed information on the experimental design of the four treatments is provided in Table 1. Herbicides and insecticides were used to control weeds and subterranean insects before soil tillage. Prior to sowing, all plots were rotovated two times to a depth of 8–10 cm, and irrigation was applied. Maize was sown by hand at a depth of 5–6 cm with 1–2 maize seeds per hole.

2.3. Carbon footprint calculation

This study was conducted to calculate the potential contribution of spring maize production to global warming. This was determined by calculating the CO_2-eq of each pattern by quantifying all GHG emissions and removals throughout the life cycle growing stage. The system boundary of this investigation included the entire life cycle from raw material acquisition of agricultural inputs to farm gates (spring maize harvest) (Fig. 2). The GHG emissions from agricultural inputs and non-CO_2 GHG emissions from farmland soil were assessed for the entire production chain of spring maize. The GHG emissions comprised the following: (1) production, storage, and transportation of agricultural inputs (e.g. seeds, fertilizers,

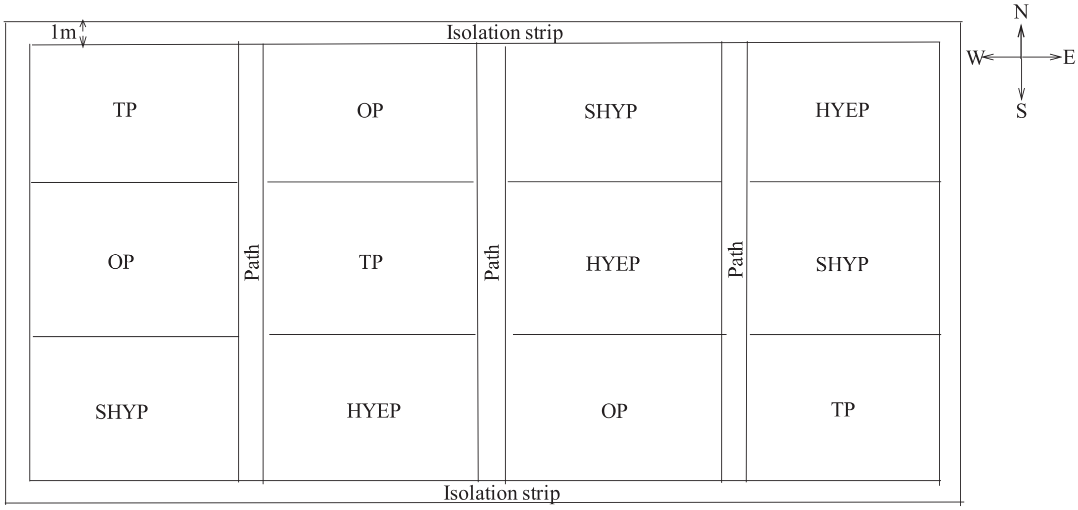

Fig. 1. Experimental design of project site. TP, traditional pattern; OP, optimal pattern; SHYP, super-higher-yield pattern; HYEP, high-yield and high-efficient pattern.

Table 1
The experimental design.

Treatments		TP [a]	OP [a]	SHYP [a]	HYEP [a]
Maize variety		Jinyu 811	Jinyu 811	Dafeng 26	Dafeng 26
Density (plant ha^{-1})		37,500	45,000	75,000	75,000
Line spacing (cm)		50:50	60:40	60:40	60:40
Row spacing (cm)		50	44–45	26–27	26–27
Basal fertilizer (kg ha^{-1})	Poultry manure [b]	–	15,000	22,500	22,500
	Compound fertilizer [c]	600	500	1000	1000
	Urea	130.5	–	–	–
Topdressing (kg ha^{-1})	Urea	325.5	325.5	450	325.5
The seeding data		Apr-30	Apr-30	Apr-30	Apr-30

[a] TP, traditional pattern; OP, optimal pattern; SHYP, super-higher-yield pattern; HYEP, high-yield and high-efficient pattern.
[b] Poultry manure were applied with rotten chicken manure before sowing.
[c] Compound fertilizers (N: P_2O_5: K_2O = 15:15:15) were applied into each plot in the study.

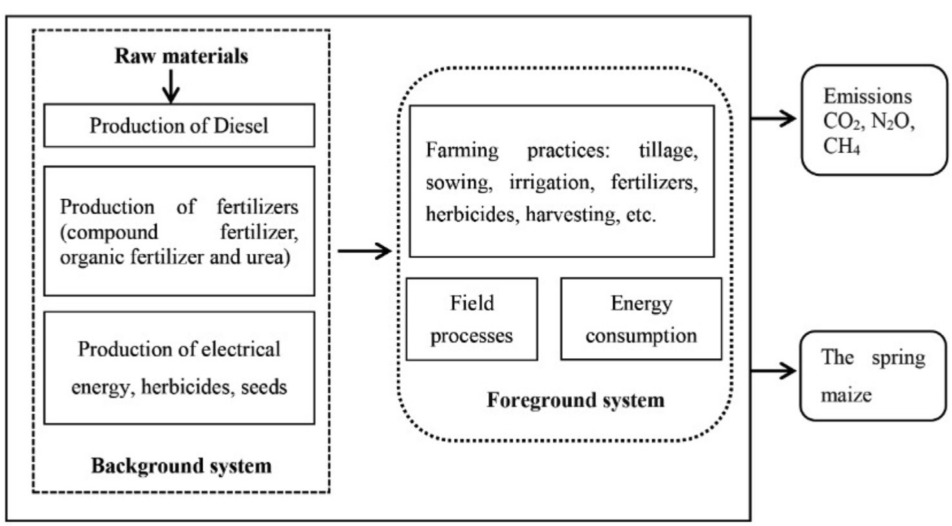

Fig. 2. The system boundary of the study.

pesticides) to the farm gate and application; (2) energy consumption of farm machinery operation (e.g., tillage, irrigation, harvest); and (3) total N_2O seasonal emissions from fields during spring maize growing period. The CH_4 emissions from dryland are negligible due to the small percentage of GHGs (Guo and Zhou, 2007). In addition, energy from human labor was not calculated due to the fact that humans respire CO_2 regardless of whether they are working (West and Marland, 2002). Here, the kg CO_2-eq kg^{-1} of spring maize grain yield was defined as the functional unit. In addition, all agricultural inputs for spring maize production are

shown in Table 2.

Tillage, fertilization, straw management, and other agricultural practices may change the soil organic carbon content and its distribution characteristics, altering soil organic carbon reserves. The CF of spring maize was determined by dividing all GHG emissions from agricultural inputs and non-GHG emissions from arable land by the grain yield of the spring maize. An estimation of the CF of spring maize production was calculated using the following Eq. (1) (Gan et al., 2012a; IOS 14067 2013):

$$CF_y = \frac{CE_{\text{total}}}{Y} \tag{1}$$

where CF_y is the total CF for each kg of spring maize grain produced (kg CO_2-eq kg^{-1} ha^{-1}); Y is the spring maize yield (kg ha^{-1}); and CE_{total} is the total GHG emissions during spring maize production (kg CO_2-eq ha^{-1}), including GHG emissions from agricultural inputs and N_2O emissions from soil. This latter factor is calculated by Eq. (2):

$$CE_{\text{total}} = CE_{inputs} + CE_{N_2O} \tag{2}$$

$$CE_{inputs} = \sum_m \left(Q_{used_m} \times \delta_m\right) \tag{3}$$

where CE_{inputs} is the indirect total amount of GHG emissions associated with agricultural inputs (kg CO_2-eq ha^{-1} $year^{-1}$); CE_{N_2O} is the cumulative amount of direct and indirect N_2O emissions converted to CO_2 equivalents (kg CO_2-eq ha^{-1} $year^{-1}$) due to N fertilizer application; Q_{used_m} is the amount of a mth individual agricultural input applied in the spring maize production process (kg ha^{-1} $year^{-1}$), including fertilizer, diesel, electrical energy, herbicides, and seed; and δ_m is the emissions factor of individual agricultural inputs (kg CO_2-eq kg^{-1}), most of which were sourced from the IKE eBalance v3.0 (IKE Environmental Technology CO., Ltd, China). The emissions factor of organic fertilizer is ~27.5 g CO_2-eq kg^{-1} (Stout, 1990).

The N_2O emissions from farmland were estimated according to the 2006 IPCC Guidelines (IPCC, 2006). The application of synthetic N fertilizer and organic fertilizer was the primary contributor of direct and indirect N_2O emissions from soil in the study (IPCC, 2006). The direct and indirect N_2O emissions from cropland were estimated using Eq. (4):

$$CE_{N_2O} = D_{N_2O} + V_{N_2O} + L_{N_2O} \tag{4}$$

where CE_{N_2O} has the same meaning as in Eq. (3); D_{N_2O} is the direct N_2O emissions from farmland (kg CO_2-eq ha^{-1} $year^{-1}$); V_{N_2O} is the amount of indirect N_2O produced from atmospheric deposition of N volatilized as NH_3 and NO_x from farmland (kg CO_2-eq ha^{-1} $year^{-1}$); and L_{N_2O} is the amount of N_2O produced from N leaching and runoff (kg CO_2-eq ha^{-1} $year^{-1}$). These values can be calculated by:

$$D_{N_2O} = (F_{SN} + F_{ON}) \times EF_1 \times \frac{44}{28} \times 298 \tag{5}$$

$$V_{N_2O} = [(F_{SN} \times Frac_{GASF}) + (F_{ON} \times Frac_{GASM})] \times EF_2 \times \frac{44}{28} \times 298 \tag{6}$$

$$L_{N_2O} = (F_{SN} + F_{ON}) \times Frac_{LEACH} \times EF_3 \times \frac{44}{28} \times 298 \tag{7}$$

where F_{SN} and F_{ON} are the amount of pure N sourced from synthetic fertilizer and organic fertilizer, respectively, during spring maize production [kg N ha^{-1}; the average pure N content of poultry manure is 2.08% in China (Li et al., 2009)]; EF_1 is the emissions factor of direct N_2O emissions due to N application (0.01 kg N_2O-N of kg^{-1} N applied); $Frac_{GASF}$ is the fraction of synthetic fertilizer N that volatilizes as NH_3 and NO_x (0.10 kg NH_3-N + NO_x-N of kg^{-1} N applied); $Frac_{GASM}$ is the fraction of organic N fertilizer that volatilizes as NH_3 and NO_x (0.20 kg N volatilized of kg^{-1} N applied); EF_2 is the emissions factor for N_2O emissions from atmospheric deposition of N on soil surfaces (0.01 kg N_2O-N of kg^{-1} NH_3-N and NO_x-N volatilized); $Frac_{LEACH}$ is the fraction of applied N/mineralized N by the loss of leaching and runoff (0.30 kg N volatilized kg^{-1} of N applied); EF_3 is the emissions factor for N_2O emissions from N leaching and runoff (0.0075 kg N_2O-N of kg^{-1} N); 44/28 is the molecular weight ratio of N_2O to N_2O-N; and 298 is the global warming potential (GWP) of N_2O relative to CO_2 over a 100-year time horizon. The above emissions factors were used according to the default values sourced from the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006).

An estimation of the CF_{SOC} of spring maize production was calculated using the following Eq. (8)

$$CF_{SOC} = \frac{CE_{\text{total}} - \Delta SOC}{Y} \tag{8}$$

where CF_{SOC} is the total CF for each kg of spring maize grain produced given the soil organic carbon into consideration (kg CO_2-eq kg^{-1} ha^{-1}); CE_{total} is the total GHG emissions during spring maize production (kg CO_2-eq ha^{-1}); ΔSOC is the variation of soil organic carbon during the maize production according to Yu et al. (2013), who estimated that the SOC storage could increase at the rate of 0.48 Mg CO_2-eq ha^{-1} yr^{-1} under current agriculture management in dryland region; Y is the spring maize yield (kg ha^{-1}).

2.4. Environmental life cycle assessment

An environmental impact assessment was used to further interpret the data. The inventory data were multiplied by characterization factors to provide indicators for the so-called environmental impact categories, including depletion of resources, global warming, acidification, eutrophication, human toxicity, and ecotoxicity. The characterization results for the sub-categories can be calculated according to Eq. (9):

$$\text{Impact category indicator}_i = \sum_j Ej \times EFi,j \tag{9}$$

where the impact category indicator i represents the indicator value per functional unit for the impact category i; E_j represents the release of emission j or consumption of resource j per functional

Table 2
The agricultural inputs amount in the spring maize production under different cultivation patterns.

Agricultural inputs	TP [a]	OP [a]	SHYP [a]	HYEP [a]
Seed (kg ha^{-1})	12.8	15.0	22.5	22.5
Compound fertilizer (kg ha^{-1})	600.0	500.0	1000.0	1000.0
Urea (kg ha^{-1})	456.0	325.5	450.0	325.5
Poultry manure (kg ha^{-1})	0	15,000	22,500	22,500
Insecticides (kg ha^{-1})	15.0	15.0	15.0	15.0
Herbicides (kg ha^{-1})	6.0	6.0	6.0	6.0
Tillage (kg ha^{-1}) [b]	35.7	35.7	35.7	35.7
Irrigation (KWh ha^{-1}) [c]	300.0	300.0	300.0	300.0
Harvest (kg ha^{-1}) [b]	38.3	38.3	38.3	38.3

[a] TP, traditional pattern; OP, optimal pattern; SHYP, super-higher-yield pattern; HYEP, high-yield and high-efficient pattern.

unit; and $EF_{i,j}$ represents the characterization factor for emission j or resource j contributing to impact category i.

The characterization factors represent the potential of a single emission or resource consumption to contribute to the respective impact category (ISO, 2000). An example of such an indicator is the global warming potential, expressed in CO_2-eq, which is derived from the rate of CO_2, CH_4, and N_2O emissions multiplied by their respective characterization factors (e.g. 1 for CO_2, 298 for N_2O). The characterization factors in this study are sourced from the study of Wang et al. (2006) for eutrophication and acidification and from Huijbregts et al. (2000) for human toxicity and eco-toxicity. IKE eBalance v3.0 is the main data source for resource consumption and emissions related to various inputs and outputs of the maize production.

After the aggregation of the inventory data into impact categories, the process of normalization of indicator results could be conducted to better understand the magnitude for each indicator result of the product system (ISO, 2000). During normalization, the indicator results per ton are related to the respective indicator results for the defined reference area (Wang et al., 2006) (in China) according to Eq. (10):

$$Ni = \frac{\mathrm{Ii}}{NVi} \tag{10}$$

where N_i represents the normalization result per functional unit for impact category i; I_i represents the indicator value per functional unit for impact category i; and NV_i represents the indicator value for a reference situation for impact category i, which is the normalization value. This study used the 1995 global per capita environmental potential for the normalization value (Huijbregts et al., 2003) in Table 3.

The environmental index '*EcoX*' can be calculated for a specific product or system under examination by multiplying the normalization result for each impact category by the respective weighting factor and summing up the weighted results as in Eq. (11):

$$EcoX = \sum_i Ni \times WFi \tag{11}$$

where *EcoX* represents the environmental index per functional unit; N_i represents the normalization result per functional unit for impact category i; and WF_i represents the weighting factor for impact category i. WF_i values, which are shown in Table 3, were derived from the study of Wang et al. (2006).

2.5. Sensitivity analysis

Sensitivity analysis is used to determine the influence of variations in assumptions on the result (BSI, 2006). In the study, the sensitivity was analyzed to identify the response of total GHG emissions to changes in agricultural inputs. In general, fertilizers contribute the most to GHG emissions in crop production; rates of organic fertilizer, compound fertilizer, and urea application among the different treatments varied by about 50%, 100%, and 38%, respectively. Therefore, the median value (50%) was chosen as an assumption and the amount of all agricultural inputs were varied from −50% to 50% to assess the sensitivity of GHG emissions to changes in agricultural inputs under different cultivation patterns.

2.6. Economic assessment of agriculture inputs under different cultivation patterns

Table 4 gives the economic data of agriculture inputs of spring maize production under different cultivation patterns. The basic data which included the cost of seed and fertilizer, etc., sourced from the experimental records.

2.7. Statistical analysis

The effects of cultivation patterns on CFs were analyzed by one-way ANOVA using the SPSS 16.0 (SPSS Inc., Chicago, IL, US) software package. The mean differences among treatments were determined by the least significance difference (LSD) at $P < 0.05$.

3. Results

3.1. Greenhouse gas emissions from agricultural inputs

Differences in the total GHGs emissions from the various agricultural inputs were observed (Fig. 3) among the different cultivation patterns. The GHG emissions from agricultural inputs were 3225.2, 3152.9, 4557.2, and 4259.7 kg CO_2-eq ha^{-1} for TP, OP, SHYP, and HYEP, respectively, during the spring maize production process. Chemical fertilizers consisting of urea and compound fertilizer were the largest contributors to the total GHG emissions of

Table 3
Normalization value and weighting factor for different impact categories.

Environment impact categories	Unit	normalization value	weighting factor
Depletion of resources	MJ yr^{-1}	56,877.88	0.15
global warming	kg CO_2-eq a^{-1}	7192.98	0.12
Acidification	kg SO_2-eq a^{-1}	56.14	0.14
Eutrophication	kg PO_4-eq a^{-1}	10.7	0.12
Human Toxicity Potential	kg 1,4 DCB-eq a^{-1}	10,000	0.14
Aquatic Eco-Toxicity Potential	kg 1,4 DCB-eq a^{-1}	315.79	0.11
Terrestrial Eco-Toxicity Potential	kg 1,4 DCB-eq a^{-1}	24.56	0.09

Table 4
The cost of agriculture inputs under different cultivation patterns.

unit/RMB ha^{-1}	Seed	Poultry manure	Compound fertilizer	Urea	pesticide	Tillage	Irrigation
TP[a]	280	0	3000	14	47	44	25
OP[a]	330	350	2500	10	47	44	25
SHYP[a]	495	525	5000	13	47	44	25
HYEP[a]	495	525	5000	10	47	44	25

a TP, traditional pattern; OP, optimal pattern; SHYP, super-higher-yield pattern; HYEP, high-yield and high-efficient pattern.

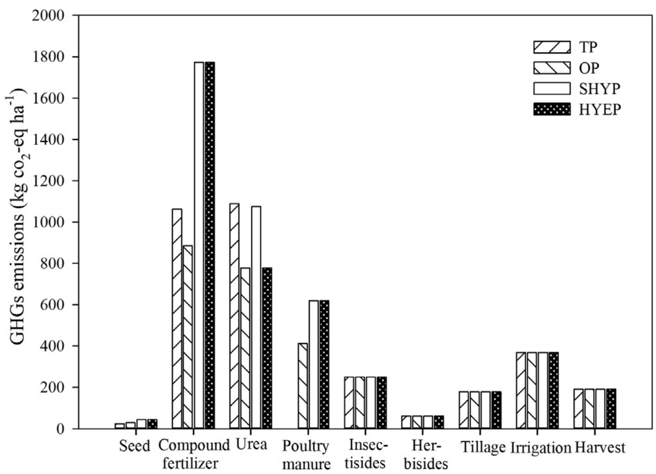

Fig. 3. Greenhouse gas (GHGs) emissions from agricultural inputs in the spring maize production under different cultivation patterns. TP, traditional pattern; OP, optimal pattern; SHYP, super-higher-yield pattern; HYEP, high-yield and high-efficient pattern.

agricultural inputs, accounting for 66.8%, 52.8%, 62.5%, and 59.9% of TP, OP, SHYP, and HYEP emissions, respectively. Notably, the percentages of GHG emissions contributed by urea and compound fertilizer differed among treatments. GHG emissions from compound fertilizer application were the greatest for HYEP and SHYP, followed by TP and then OP, while those from urea were greatest for TP, followed by SHYP, and then OP and HYEP. After chemical fertilizers, the GHG emissions associated with poultry manure application were the next highest contributor to total emissions from agricultural inputs.

After the fertilizers, irrigation was the second greatest contributor to total GHG emissions of agricultural inputs. The percentages of GHG emissions contributed by irrigation were 11.4%, 11.7%, 8.1%, and 8.7% for TP, OP, SHYP, and HYEP, respectively. The GHG emissions from machinery operations, including tillage and harvest, accounted for 368.7 kg CO_2-eq ha^{-1} for all treatments in the study. In addition, insecticides contributed to a larger percentage of the GHG emissions than herbicides among the agricultural inputs. The smallest contributor to total GHG emissions among the agricultural inputs was the maize seed application.

3.2. Carbon footprint of spring maize production

The yield of spring maize among treatments ranged from 10.7 to 17.0 Mg ha^{-1}, with the greatest yield for SHYP, followed by HYEP, OP, and TP (Fig. 4A). A significant difference in maize yield was observed between each pair of treatments ($P < 0.05$) except for between OP and HYEP. Differences in the CF of spring maize at yield-scale were observed across cultivation patterns (Fig. 4B). The CF at yield-scale ranged from 0.48 to 0.64 kg CO_2-eq kg^{-1}, with the highest CF for HYEP, followed by SHYP, OP, and TP. The CFs of spring maize under HYEP and SHYP were significantly higher than those under TP and OP ($P < 0.05$), while no significant differences in CF were observed between SHYP and HYEP or between TP and OP. With the soil organic carbon storage into calculation, the CF of spring maize ranged from 0.43 to 0.61 kg CO_2-eq kg^{-1}, decreasing 4.8%–9.4% (Fig. 4C).

The percentages of the CF components for spring maize production were compared across different cultivation patterns (Fig. 4D). N_2O emissions from soil were the main contributors to the CF of spring maize, accounting for 36.8–54.0% of the CF among different treatments. Next, fertilizers contributed to 36.8–49.4% of the CF of spring maize production at yield-scale. In particular, chemical fertilizers, including compound fertilizer and urea, contributed to 25.0–42.2% of the CF among different cultivation patterns, while poultry manure contributed to 6.2–6.7% of the CF among all treatments except for TP. Percentages for irrigation and pesticides ranged from 3.7% to 7.2% and from 3.1% to 6.1%, respectively. Other agricultural inputs, e.g., machinery operations and seeds input, contributed only minimally to the CF of spring maize production.

3.3. Environmental impact assessment of spring maize production

The environment impact categories for the spring maize production under different cultivation patterns are showed in Table 5. Within the impact category "depletion of abiotic resources", energy consumption ranged from 5434.82 to 8078.92 MJ t^{-1} among different cultivation patterns. The acidification potential of the maize production system ranged from 11.62 to 16.44 as kg SO_2-eq t^{-1} grain, the order of which was HYEP > SHYP > TP > OP. Table 6 gives the normalization results for the impact categories of spring maize production under different cultivation patterns. The results indicated that at different cultivation patterns acidification and eutrophication were relevant environmental impact connected to the production of 1 ton of spring maize production. The normalization results of acidification and eutrophication among different cultivation patterns ranged from 0.207 to 0.293 and 0.204 to 0.289, respectively, which were higher than the impact index of other environment categories, indicating that acidification and eutrophication were serious environmental problems stemming from maize production under all cultivation patterns. The normalization value of terrestrial eco-toxicity potential ranged from 0.142 to 0.227, which resulted mainly from the use of pesticides. The normalization value of global warming ranged from 0.061 to 0.097, which was higher than the values of human and aquatic eco-toxicity potential. Table 7 shows the aggregated environmental indicators (EcoX) per ton of grain for the maize production under different cultivation patterns. The lower environmental impact was calculated for TP and OP (0.107 and 0.095, EcoX/ton grain). The EcoX value for SHYP amounted to 0.110, which is 11.8% lower than for HYEP. The EcoX values for different cultivation patterns dominated by acidification and eutrophication (51.8%–61.7% of the total value), compared to which the global warming took comparatively small percentage ranged from 6.8% to 9.5%.

3.4. Sensitivity of total GHG emissions to different agricultural inputs

An analysis of the sensitivity of total GHG emissions to different agricultural inputs was conducted for the four cultivation patterns (Fig. 5). For TP treatment, total GHG emissions were the most sensitive to urea, followed by compound fertilizer, irrigation, harvest, and tillage. Total GHG emissions decreased to 3898.88 kg CO_2-eq ha^{-1} when the amount of urea was reduced by 50% and increased to 6309.10 kg CO_2-eq ha^{-1} when the amount of urea increased by 50% under TP treatment (Fig. 5A). In contrast, total GHG emissions were the most sensitive to organic fertilizer under the OP, SHYP, and HYEP treatments (Fig. 5B, C, D). After organic fertilizer, urea and compound fertilizer were the next most important agricultural inputs with regards to total GHG emissions in spring maize production. The above results indicate that changes in the amount of fertilizer used, including organic fertilizer, compound fertilizer, and urea, strongly affect total GHG emissions in spring maize production.

3.5. Economic assessment of different cultivation patterns

The total cost for implementing the different cultivation

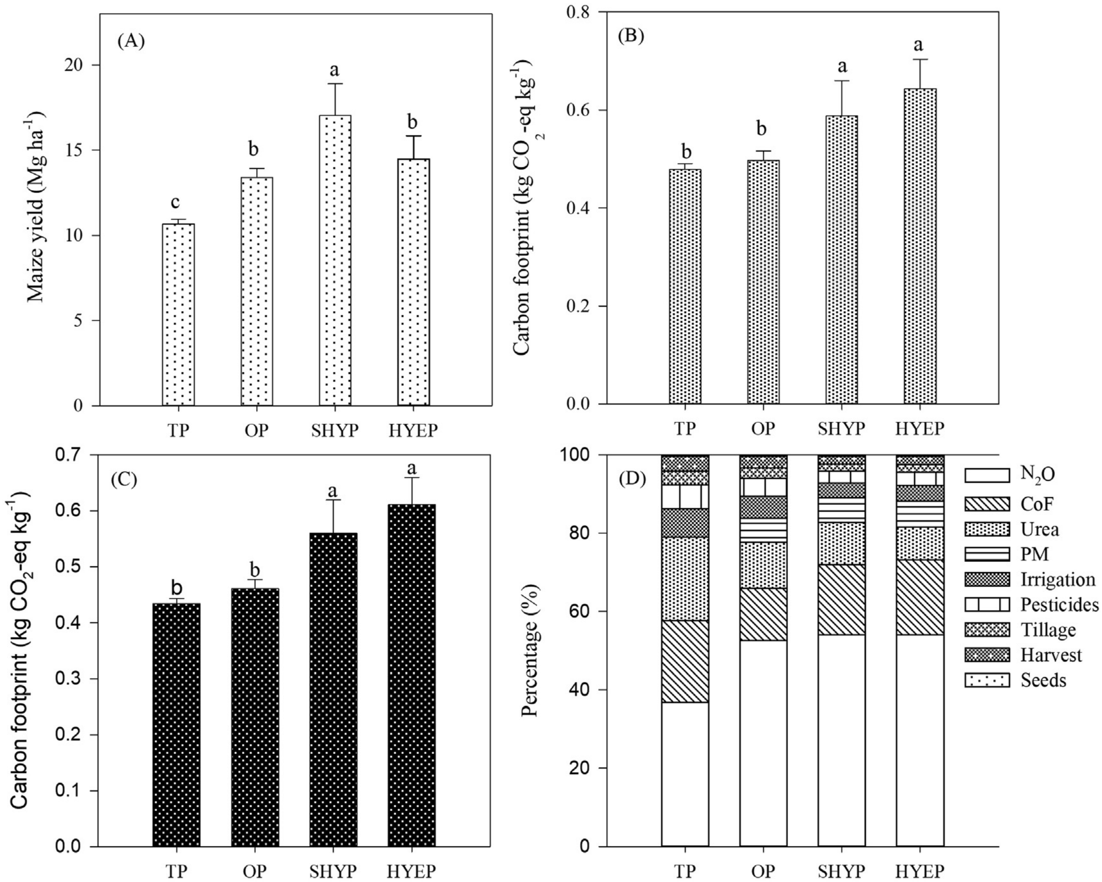

Fig. 4. The maize yield (A) carbon footprint (B) of spring maize, carbon footprint with soil organic carbon storage into consideration (C) and its component percentage (D) under different cultivation patterns. TP, traditional pattern; OP, optimal pattern; SHYP, super-higher-yield pattern; HYEP, high-yield and high-efficient pattern. The lowercase letters indicate statistical difference among different treatments at $P < 0.05$. CoF in the legend indicates compound fertilizer, PM indicates poultry manure, and pesticides includes insecticides and herbicides.

Table 5
The environment impact categories for the spring maize production under different cultivation patterns.

Environment impact categories	Unit	TP [a]	OP [a]	SHYP [a]	HYEP [a]
Depletion of resources	MJ t^{-1}	8078.92	5434.82	6635.40	7252.61
global warming	kg CO_2-eq t^{-1}	435.36	533.96	630.35	699.43
Acidification	kg SO_2-eq t^{-1}	12.28	11.62	14.82	16.44
Eutrophication	kg PO_4-eq t^{-1}	2.19	2.18	2.78	3.09
Human Toxicity Potential	kg 1,4 DCB-eq t^{-1}	0.41	0.33	0.26	0.30
fresh water Aquatic EcoToxicity Potential	kg 1,4 DCB-eq t^{-1}	6.69	5.34	4.19	4.93
Terrestrial EcoToxicity Potential	kg 1,4 DCB-eq t^{-1}	5.59	4.45	3.50	4.12

[a] TP, traditional pattern; OP, optimal pattern; SHYP, super-higher-yield pattern; HYEP, high-yield and high-efficient pattern.

Table 6
Life cycle environmental impact index of spring maize production under different cultivation patterns.

Environment impact categories	TP [a]	OP [a]	SHYP [a]	HYEP [a]
Depletion of resources	0.142	0.096	0.117	0.128
global warming	0.061	0.074	0.088	0.097
Acidification	0.219	0.207	0.264	0.293
Eutrophication	0.205	0.204	0.260	0.289
Human Toxicity Potential	0.000	0.000	0.000	0.000
Aquatic Eco-Toxicity Potential	0.021	0.017	0.013	0.016
Terrestrial Eco-Toxicity Potential	0.227	0.181	0.142	0.168

[a] TP, traditional pattern; OP, optimal pattern; SHYP, super-higher-yield pattern; HYEP, high-yield and high-efficient pattern.

Table 7
Life cycle environmental impact evaluation results of maize production system.

Environment impact categories	TP [a]	OP [a]	SHYP [a]	HYEP [a]
Depletion of resources	0.021	0.014	0.017	0.019
global warming	0.007	0.009	0.011	0.012
Acidification	0.031	0.029	0.037	0.041
Eutrophication	0.025	0.024	0.031	0.035
Human Toxicity Potential	0.000	0.000	0.000	0.000
Aquatic Eco-Toxicity Potential	0.002	0.002	0.001	0.002
Terrestrial Eco-Toxicity Potential	0.020	0.016	0.013	0.015
aggregate index	0.107	0.095	0.110	0.123

[a] TP, traditional pattern; OP, optimal pattern; SHYP, super-higher-yield pattern; HYEP, high-yield and high-efficient pattern.

patterns ranged from 7276.1 to 16,442.1 RMB ha^{-1}, with the highest cost for SHYP, followed by HYEP, OP, and TP (Fig. 6A). Among the different agricultural inputs, fertilizer application was a major contributor to the total cost of spring maize production, accounting for 72.3%–85.0%. After the fertilizer application, land leasing contributed to 9.3–21.2% of the total cost of spring maize production. The total income for spring maize production among treatments ranged from 19,206.45 to 30,653.1 RMB ha^{-1}, with the greatest income for SHYP, followed by HYEP, OP, and TP (Fig. 6B). The net income of SHYP was 14,211 RMB ha^{-1}, which was the highest among the cultivation patterns (Fig. 6C), followed by OP, TP, and HYEP.

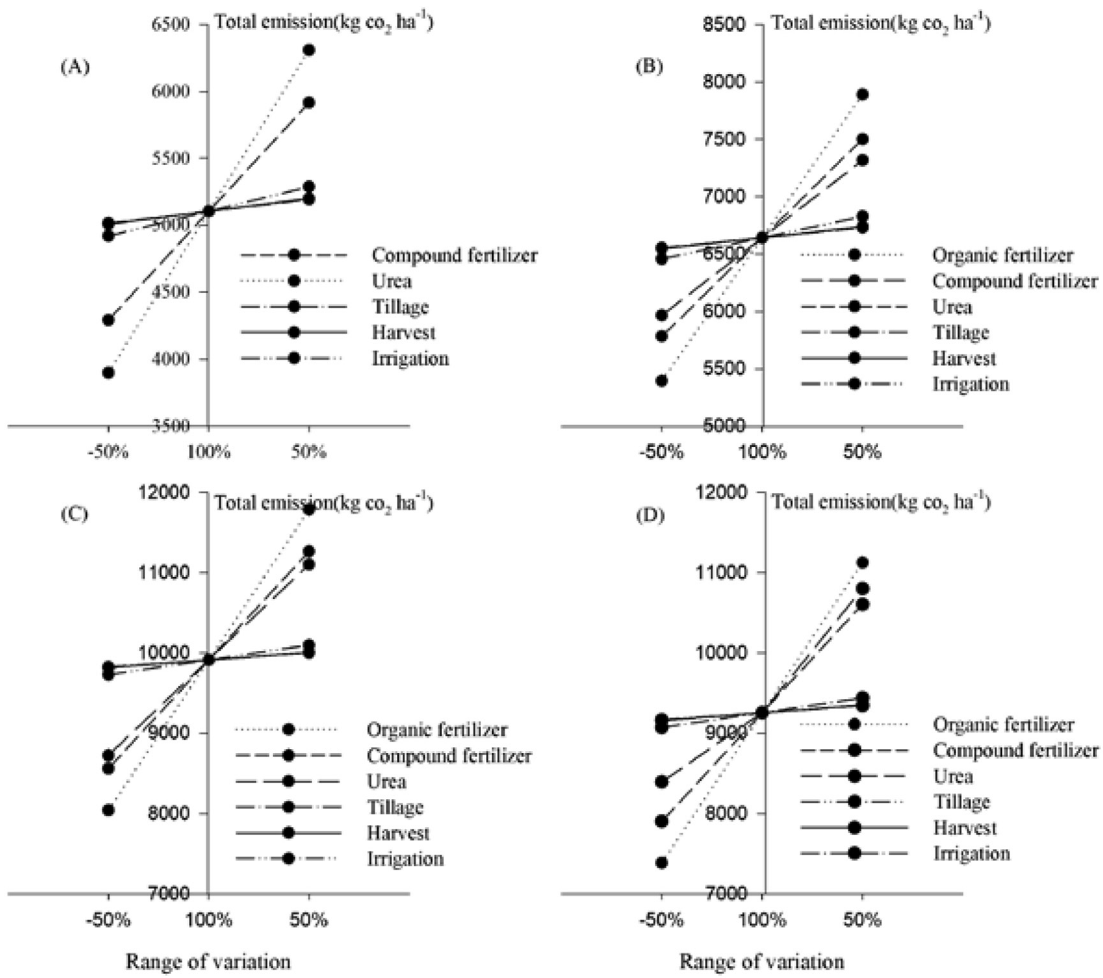

Fig. 5. Sensitive analysis of different agricultural inputs to total GHGs emissions under different cultivation patterns. TP (A), traditional pattern; OP (B), optimal pattern; SHYP (C), super-higher-yield pattern; HYEP (D), high-yield and high-efficient pattern.

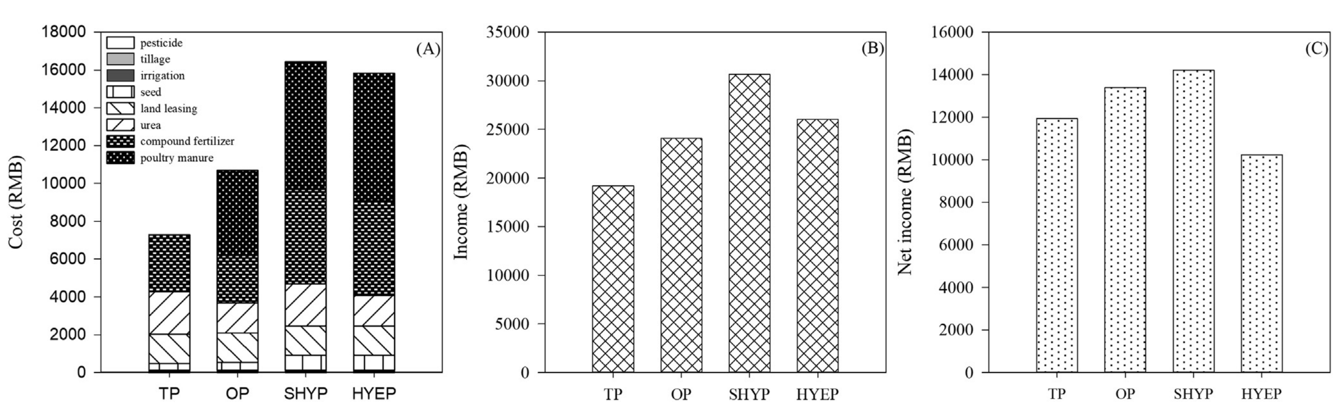

Fig. 6. Financial information of different cultivation patterns. TP, traditional pattern; OP, optimal pattern; SHYP, super-higher-yield pattern; HYEP, high-yield and high-efficient pattern. A, B, C represent total cost, total income and net income of maize production respectively.

4. Discussion

4.1. GHG emissions associated with agricultural inputs

In this study, the GHG emissions from agricultural inputs ranged from 3152.9 to 4557.2 kg CO_2-eq ha^{-1} yr^{-1} during spring maize production, which was higher than that reported by Shi et al. (2011). This may be due to differences in cropping systems, farm management, and calculation methods between the two studies. Additional agricultural inputs (e.g., fertilizers) were applied in the current study to obtain higher maize yields in the spring maize cropping system compared to those in the summer maize cropping system. The optimization of farm management practices, e.g., planting population, tillage, variety, and fertilizer, can keep GHG emissions low in agricultural systems (Grace et al., 2011). Technologies were integrated with different farm management practices in the present study, and the results indicated that changes in farm management practices could affect GHG emissions associated with agricultural inputs. In addition, the LCA method was adopted to calculate GHG emissions during the spring maize production, while the input-output method was applied by Shi et al. (2011).

Fertilizer was the largest contributor to the GHG emissions of agricultural inputs during spring maize production, similar to results from other studies (Cheng et al., 2011; Xue et al., 2014). The GHG emissions from all fertilizers varied between TP (2153.0 kg CO_2-eq ha^{-1}) and OP (2076.4 kg CO_2-eq ha^{-1}) in this study, indicating that the replacement of chemical fertilizer with poultry manure can mitigate GHG emissions in agricultural systems. Larger GHG emissions for SHYP and HYEP were observed than for TP and OP due to the greater amounts of fertilizers applied. The GHG emissions from agricultural inputs for SHYP and HYEP differed slightly due to the different amounts of topdressing applied. Reductions in the rate of fertilizer application could be an effective solution for minimizing GHG emissions derived from agricultural inputs (Wang et al., 2015). According to a report by the Central People's Government of the People's Republic of China, further implementation of the “Nation Fertilization According to Soil Test Result” project was designed to decrease the rate of fertilizer application by ~20% per unit area, which would decrease GHG emissions from agricultural production. In addition, pesticide application was a small contributor to GHG emissions in spring maize production in this study. However, larger amounts of pesticides are often applied to crop production, leading to ground water pollution and pesticide residues in food, which poses a threat to human health (Norc, 1994; Wiles et al., 1994).

4.2. Carbon footprint of spring maize production

Increasing awareness of climate change is spurring additional investigations into how agricultural systems can be better managed to ensure production in sufficient quantities with minimal environmental impacts (Tilman et al., 2011; Garnett et al., 2013). Balancing the environmental burden with crop production is of great importance in the sustainable development of agriculture. The CF at yield-scale can be used to assess the combined effect of various inputs on GHG emissions and crop yield. A higher CF at yield-scale does not therefore necessarily mean larger absolute GHG emissions, as the value of CF is also dependent on grain yields. In our study, the CF at yield-scale among different cultivation patterns ranged from 0.48 to 0.64 kg CO_2-eq kg^{-1}, with the highest value for HYEP, followed by SHYP, OP, and TP. There are some differences between our findings and other published results (Cheng et al., 2015; Wang et al., 2015). The mean CF value of maize at yield-scale was estimated to be 0.44 kg CO_2-eq kg^{-1} according to a national statistical dataset in China (Cheng et al., 2015). The CF values of summer maize ranged from 0.51 to 1.06 kg CO_2-eq kg^{-1}, increasing with larger amounts of N fertilizer (Wang et al., 2015). Differences in the above CF values can be explained by differences in the cropping systems, farm management practices, and calculation methods.

The maize yield for OP was higher than that for TP, while there was no significant difference between their respective CF values. This indicates that replacing chemical fertilizer with organic fertilizer can significantly improve crop yield without affecting the CF of spring maize. Differences in planting density resulting from adjusting line and row spacing may also explain this result. An increase in grain yield plays an important role in reducing the CF at yield-scale (Gan et al., 2012b). In addition, no significant difference in CF at yield-scale was observed between SHYP and HYEP; however, the yield of spring maize for SHYP was significantly higher than that for HYEP due to the larger amount of urea used for topdressing in SHYP ($P < 0.05$). Higher GHG emissions under SHYP caused by the higher urea level could explain the above result. Compared to OP, SHYP exhibited both higher crop yield and CF due to a higher planting density and larger amounts of fertilizers. Reducing the CF of spring maize without decreasing yield is a critical issue that urgently needs to be addressed in the region. It is necessary to lower the CF of agricultural systems through the adjustment of farming management practices, e.g., crop variety, planting density, fertilizer use, which should be investigated in future research.

Intensive agriculture, with high input-high output patterns (e.g., SHYP, HYEP), remains a developing trend in the short term to obtain higher yields and feed the ever-growing human population in China (Ling and Jiang, 2010). The use of fertilizers, pesticides, and diesel oil associated with machinery operation is increasing rapidly in intensive agricultural systems, resulting in larger GHG emissions (Dusenbury et al., 2008; Guo et al., 2010). However, intensive agriculture is not sustainable in the future due to the excess resources consumed and environmental issues. In our study, the CFs for SHYP and HYEP, which included a higher planting density and higher rate of fertilizer use, were significantly greater than those for TP and OP. Intensive cropping systems with higher inputs under the SHYP and HYEP treatments obtained higher yields of spring maize compared to those under TP and OP treatments; however, this was accompanied by higher GHG emissions, exacerbating climate change. Achieving high yields and low GHG emissions of inputs in intensive cropping systems are not conflicting goals (Grassini and Cassman, 2012). The implementation of C-friendly strategies is necessary for the sustainable development of agriculture, and this can be achieved by optimizing tillage management practices, improving water and fertilizer management, and choosing better crop varieties. The adoption of no-till practices could reduce the CF at yield-scale by decreasing non-CO_2 GHG emissions from field soil compared to the use of plow tillage and rotary tillage (Xue et al., 2014). Sulfur-coated urea and the urea with added dicyandiamide treatment could reduce total GHG emissions in spring maize production and the CF at yield-scale compared with those of conventional fertilization (Duan et al., 2014). The CF at yield-scale decreases with reductions in the rate of N fertilizer (Wang et al., 2015), and appropriate amounts of N fertilizer and improvements in fertilizer use efficiency could maintain crop yields while reducing CFs in agricultural production systems.

The LCA method was used to calculate the CF of spring maize under different cultivation patterns in this study. This is a suitable method for assessing the environmental burden expected with the input-output method. The exhaustive list and detailed dataset in the whole production process of product in detail are helpful to get a receivable result. Most data for agricultural inputs were collected from the experimental results in this study, while the N_2O

emissions from field soil were estimated according to the method supplied by the IPCC (2006). There must be a distinction between the estimated value and the factual value with regard to N_2O emissions. However, the general CF trends did not vary among treatments.

In addition, the PAS model (BSI and Carbon Trust, 2011) indicates that an assessment of CF must include GHG emissions arising from direct land-use change but should not include those arising from soil carbon changes in existing agricultural systems. The question of whether to include soil carbon changes due to farming practices in the calculation of the CFs of grain products remains controversial (Gan et al., 2012a). Some studies have considered the change in soil organic carbon storage in their assessment of the CF of a crop product, which resulted in a reduction in the CF of wheat and rice with an increase in soil organic carbon storage under different farm management practices (Gan et al., 2012a; Xue et al., 2014). According to Yu et al. (2013), the soil organic carbon storage could increase at the rate of 0.48 Mg CO_2-eq ha^{-1} yr^{-1} under current agriculture management in dryland region, based on which the CF of the four cultivation patterns would range from 0.43 to 0.61 kg CO_2-eq kg^{-1}. On the basis of soil organic carbon stock variation, the CF of the different cultivation patterns decreased 4.8%–9.4%. In addition, organic fertilizer application is one of the most predominant management practices causing soil organic carbon changes due to the directly added carbon into soil (Maillard and Angers, 2014). Therefore, compared to chemical fertilizer, organic fertilizer could feasibly increase soil organic carbon storage (Gong et al., 2009; Han et al., 2016), which would result in an additional reduction in the CF of SHYP and HYEP. In this case, the main conclusion of this study will not be changed. However, a potential limitation of this study is that the soil organic carbon storage variation is not clear among the different cultivation patterns.

Overall, more accurate results for particular maize production systems can be determined if experimental measurements on N_2O emissions and soil organic carbon storage are performed. From another point of view, the purpose of this study was to compare different cultivation patterns, which are usually used at multiple locations where soil properties and climate conditions may differ. In order to compare the CF of different cultivation patterns instead of the definitive CF values of a particular production system at a particular experimental site, thus there are no experimental measurements for N_2O and soil organic carbon storage. Therefore, this study may provide useful reference information for the evaluation of GHG emissions among different cultivation patterns.

4.3. Environmental impact assessment of spring maize production

The life cycle environmental impact aggregate indexes of different cultivation patterns were 0.107, 0.095, 0.110, and 0.123 for TP, OP, SHYP, and HYEP, respectively. Maize production involves two environmental hotspots, acidification and eutrophication. Thus, the greatest potential to minimize the environmental impact per ton of grain is to use nitrogen fertilizers with low NH_3 volatilization rates, which are most responsible for acidification and eutrophication. The global warming potential of maize production took only a small percentage of the total value, ranging from 0.007 to 0.012. Therefore, in this regard, according to the results of environmental assessment, global warming potential of maize production in this study contributes less to environment impact. However, to some degree the research of global warming potential is still of great importance to environmental improvement. From this study, it could be concluded that a good environmental performance in maize production could be achieved by maintaining optimum yields and applying fertilizer appropriately in order to minimize contaminants emissions.

4.4. The composition of carbon footprint

In this study, the N_2O emissions from field soil accounted for 36.8–54.0% of the CF of the spring maize production process. Soil N_2O is mainly generated through nitrification and denitrification associated with N fertilizer application. Reducing N_2O emissions in agricultural production systems is the key to reducing the CF of a crop product. N fertilizer application was the main cause of N_2O emissions from soil. Therefore, reducing the N fertilizer rate in crop production should be a direct way of reducing the soil N_2O emissions. The adoption of recommended management practices (RMPs; e.g., conservation tillage) could be an appropriate solution for reducing soil N_2O emissions due to changes in the soil microenvironment. Some farming practices (e.g., the use of nitrification inhibitors) can suppress the conversion of NH_4^+ to NO_3. Compared with chisel tillage and moldboard plow tillage, eliminating tillage can reduce soil N_2O emissions and increase CH_4 oxidation by decreasing the bulk density of the surface soil in continuous corn cropping systems (Ussiri et al., 2009). The N_2O emissions were the lowest for TP, followed by OP, HYEP, and SHYP; this may be attributed to differences in N fertilizer inputs. After the N_2O emissions from the soil, fertilizer application was the second largest contributor to the CF of spring maize. Decreasing the rate of fertilizer use and increasing the fertilizer use efficiency would potentially reduce the CF of spring maize. Other agricultural inputs only contributed in small amounts to the CF of spring maize. In contrast, Wang et al. (2015) found that electricity for irrigation was the main contributor to the CF in the North China Plain; however, this study differed from ours in terms of the amount of fertilizer and poultry manure used. Another reason for this difference may be that the N_2O emissions were collected by the static chamber method in Wang's study (Wang et al., 2015), while we used the IPCC method, which includes direct and indirect N_2O emissions.

5. Conclusion

This study assessed the impacts of different cultivation patterns on the CF and its components of spring maize production to identify C-friendly and cleaner cultivation technologies in the Loess Plateau, China. The data presented in our study showed that total GHG emissions from agricultural inputs ranged from 3152.9 to 4557.2 kg CO_2-eq ha^{-1} among different cultivation patterns, most of which (>65%) was attributed to fertilizer application. Decreasing the amount of fertilizer used and increasing the fertilizer use efficiency represent potential solutions for reducing GHG emissions in spring maize production. Moreover, the yield of spring maize ranged from 10.7 to 17.0 Mg ha^{-1}, with highest yield for SHYP, followed by HYEP, OP, and TP. In contrast, the CF at yield-scale ranged from 0.48 to 0.64 kg CO_2-eq kg^{-1}, with the highest value for HYEP, followed by SHYP, OP, and TP. SHYP, with its higher yield, output value and lower CF, represents a possible C-friendly cultivation technology, balancing the environmental burden and crop production; however, additional research is still needed to further reduce GHG emissions and increase crop yield. Furthermore, soil N_2O emissions and fertilizer application were the primary contributors to the CF of spring maize. Reductions in fertilizer use, especially N fertilizer, could play a critical role in mitigating N_2O emissions to lower the CF of spring maize production. Thus, relevant policies should be enacted to further develop sustainable agricultural practices. Another conclusion could be drawn that acidification and eutrophication were environmental hotspots of maize production. Therefore, improved technology could be explored for fewer NH_3 and NO_X emissions from the fertilizer application and the production of agricultural materials.

Overall, changes in the cultivation pattern of spring maize that

involve integrating planting density, fertilizer application, and crop variety could provide potential solutions for the development of C-friendly technologies, ensure food safety and mitigating GHG emissions in the future.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.jclepro.2018.02.184.

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